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THE ANALYSIS OF THE STRESS-STRAIN STATE OF THE SYSTEM «BASEMENT - PILE FOUNDATION – STRUCTURE» CONSIDERING SWELLING PROPERTIES OF SOILS

This work analyzes factors affecting swelling soils and presents a calculation algorithm of structure on swelling soils base for the plane problem. In this work an analysis of the factors influencing the swelling of soils is made, the algorithm for calculating the structure with the base with swellable soils for a plane problem is given. At the same time, the swelling process is considered as an additional influence, close in nature to temperature, and the swelling soil is considered a material having orthotropic properties. The value of the relative swelling depends on the level of the stress state, while the value of the main stresses is compared with the magnitude of the pressure of swelling. Therefore, to determine the deformation characteristics of the swelling soil, several variants of the stressed state of the soil have to be considered. The effectiveness of the obtained solution has been verified according to the example for pile foundations.

Keywords: *swelling soils, shrinkage of swelling soils, orthotropic properties, final element method, system «basement – pile foundation – structure».*

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АНАЛІЗ НАПРУЖЕНО-ДЕФОРМОВАНОГО СТАНУ СИСТЕМИ «ОСНОВА – ПАЛЬОВИЙ ФУНДАМЕНТ – СПОРУДА» З УРАХУВАННЯМ ВЛАСТИВОСТЕЙ НАБУХАЮЧИХ ГРУНТІВ

Виконано аналіз факторів, що впливають на набухання ґрунтів, приведено алгоритм розрахунку споруди з основою з набухаючими ґрунтами для плоскої задачі. При цьому процес набуханняураховано як додатковий вплив, а набухаючий ґрунт розглядається як матеріал, що має ортотропні властивості. Доведено, що величина відносного набухання залежить від рівня напруженого стану, при цьому величина головних напруг порівнюється з величиною тиску набухання. Для визначення деформаційних характеристик набухаючого грунту доводиться розглядати кілька варіантів напруженого стану ґрунту. Ефективність отриманого рішення перевірено на прикладі для пальових фундаментів.

Ключові слова: *набухаючі ґрунти, усадка набухаючих ґрунтів, ортотропні властивості, метод скінчених елементів, система «основа – пальовий фундамент – споруда».*

Introduction. Swelling soils are widespread. Such soils are common in Egypt, Burma, USA, Canada, South Africa, Ethiopia, Sudan, Iraq, Syria, and in India more than 30% of the territory is occupied by so-called cotton soils. In the CIS countries such soils are found in Kazakhstan, Georgia, Azerbaijan, Moldova, Russia (the Volga region, the North Caucasus and other regions), Ukraine (Crimea, Kupyansk, Kharkov, Poltava, etc.).

A characteristic feature of swelling soils with soaking is sharp increase in their volume and decrease in their load capacity, which leads to considerable deformations in the structure. Therefore, when projecting, it is necessary to consider the effect of swelling on the entire system «base-foundation-structure» for more reliable exploitation [7 – 10]. Existing norms, unfortunately, do not allow to create such a model and advise to calculate deformations from external loads separately from deformation of soil swelling.

A review of the latest sources of research and publications. In work [1] the method of finding characteristics of swelling soils for calculation of the system «basement – foundation – construction» was obtained. An algorithm for calculating the «basement – foundation – structure» system on swelling soils is given, considering the orthotropic properties of these soils for a planar problem. It is proposed to represent a soil massif consisting of swelling soils in the form of a linearly deformed medium, swelling of the base to be taken into account as an additional effect that is close in nature to temperature, and the swelling soil is considered as a material possessing orthotropic properties [2, 3, 6].

Allocation of previously unresolved parts of a common problem. This method allows considering the effect of swelling on the SDC plate foundation more accurately. It is necessary to check the effectiveness of the solution for pile foundations.

Formulation of the problem. Improvement of the soil swelling registration algorithm for SDC system «basement – pile foundation – construction».

Main material and results.

1. Factors affecting the swelling of clayey soils

Swelling soils include clayey deposits, the characteristic feature of which is the increased density and high content (65–85%) of clay particles with a particle size of less than 0,005 mm. In natural occurrence, these soils (clays) are characterized by firm and turgid consistency at a specific gravity from 19,5 to 20,5 kN / m^3. The porosity of soils is in the range from 41 to 48%, with a humidity of 15–18% in the roof and 25–30% in the middle layers and the base of the strata. As a result of the moistening of these clays, their volume increases by 12–25%, and in some cases by 30–36%. As a result of swelling, the specific gravity of clays decreases to 17,7–18,7 kN / m^3, and the porosity increases to 50–58%. The moisture content of the soil increases to 36–48% and indicates the transition of clays to plastic state, which sharply reduces their bearing capacity. The value of the normal clay swelling forces in natural occurrence reaches 350–400 kPa under the pile face, and 30–37 kPa (tangential) along the lateral surface of the piles. Disintegrating when swelling, the clay raises the thickness of the overlying coverslips, which, in turn, tends to raise the foundation slab or the end of the piles.

2. Determination of swelling soils characteristics

The basic relationship for the magnitude of soil swelling deformation is taken according to Sorochan E.A. [4]:

$$\underset{i=1,2,3}{\varepsilon} = \varepsilon_i^y + \varepsilon_{i,sw} + \varepsilon_{i,sh}\,, \qquad (1)$$

where ε_i^y – major deformations at the base of stresses in the ground;

$\varepsilon_{i,sw}$ – swelling deformations depending on changes in humidity and main stresses, the ratio [4]:

$$\varepsilon_{\substack{i,sw \\ i=1,2,3}} = m \cdot \Delta w \left(1 - \frac{P}{p_{sw}}\right), \tag{2}$$

where m – coefficient that takes into account the swelling properties of soils and determined experimentally;

Δw – change in soil moisture;

P_{sw} – pressure of swelling;

P – pressure in the direction of swelling.

It is assumed that the dependence of the swelling deformation on pressure and humidity is linear. The coefficient m is similar to the coefficient of thermal expansion. In addition, it considers the properties of the swelling soil.

3. Allowance for the anisotropic properties of swelling soils when calculating the system «base-foundation-structure» under conditions of planar deformation

The value of the relative swelling depends on the level of the stress state, while for σ_x, $\sigma_z < -P_{sw}$ – swelling does not occur. Therefore, to determine the deformation characteristics of the swelling soil, several variations of soil stressed state have to be considered.

For a planar problem, it can be distinguished 9 variants of stresses combination which conditions [1]:

– $\sigma_z > 0$ and $\sigma_x > 0$;
– $\sigma_z < -P_{sw}$ and $-P_{sw} < \sigma_x < 0$;
– $\sigma_x < -P_{sw}$ and $-P_{sw} < \sigma_z < 0$;
– $-P_{sw} < \sigma_z < 0$ and $-P_{sw} < \sigma_x < 0$;
– $\sigma_x > 0$ and $-P_{sw} < \sigma_z < 0$;
– $-P_{sw} < \sigma_x < 0$ and $\sigma_z > 0$;
– $\sigma_x < -P_{sw}$ and $\sigma_z > 0$;
– $\sigma_x > 0$, $\sigma_z < -P_{sw}$;
– $\sigma_x < -P_{sw}$ and $\sigma_z < -P_{sw}$,.

1) $\sigma_z > 0$ and $\sigma_x > 0$

$$E_{np} = \frac{E}{1-\mu^2}, \qquad \mu_{np} = \frac{\mu}{1-\mu}, \tag{3}$$

where E – modulus of soil deformation;

μ – Poisson's ratio.

2) $\sigma_z < -P_{sw}$ and $-P_{sw} < \sigma_x < 0$.

Let

$$\frac{P_{sw}}{P_{sw} + Ekm\Delta w} = \alpha,$$

Then

$$E_x^{np} = \frac{1}{\frac{1-\mu^2\alpha}{E} + \frac{km\Delta w}{P_{sw}}} \quad \text{(a)} \qquad \mu_{xz}^{np} = \frac{\mu + \alpha\mu^2}{1-\mu^2\alpha + E\frac{km\Delta w}{P_{sw}}} \quad \text{(b)}$$

$$E_z^{np} = \frac{E}{1-\mu^2\alpha} \quad \text{(c)} \qquad \mu_{zx}^{np} = \frac{\mu + \mu^2\alpha}{1-\mu^2\alpha} \quad \text{(d)} \tag{4}$$

where P_{sw} – pressure of swelling;

m – coefficient determined experimentally;

Δw – change in soil moisture.

The swelling soil acquires orthotropic properties with deformation characteristics, determined by formulas (a) – (d).

3) $\sigma_x < - P_{sw}$ and $- P_{sw} < \sigma_z < 0$.

$$E_z^{np} = \frac{1}{\frac{1-\mu^2\alpha}{E} + \frac{km\Delta w}{P_{sw}}} \quad \text{(a)} \qquad \mu_{zx}^{np} = \frac{\mu + \alpha\mu^2}{1-\mu^2\alpha + E\frac{km\Delta w}{P_{sw}}} \quad \text{(b)}$$

$$E_x^{np} = \frac{E}{1-\mu^2\alpha} \quad \text{(c)} \qquad \mu_{xz}^{np} = \frac{\mu + \mu^2\alpha}{1-\mu^2\alpha} \quad \text{(d)} \tag{5}$$

The swelling soil acquires orthotropic properties with deformation characteristics, determined by formulas (a) – (d).

4) $- P_{sw} < \sigma_z < 0$, $- P_{sw} < \sigma_x < 0$.

$$E_z^{np} = \frac{1}{\frac{1-\mu^2\alpha}{E} + \frac{km\Delta w}{P_{sw}}} \quad \text{(a)} \qquad \mu_{zx}^{np} = \frac{\mu + \alpha\mu^2}{1-\mu^2\alpha + E\frac{km\Delta w}{P_{sw}}} \quad \text{(b)}$$

$$E_x^{np} = \frac{1}{\frac{1-\mu^2\alpha}{E} + \frac{km\Delta w}{P_{sw}}} \quad \text{(c)} \qquad \mu_{xz}^{np} = \frac{\mu + \alpha\mu^2}{1-\mu^2\alpha + E\frac{km\Delta w}{P_{sw}}} \quad \text{(d)} \tag{6}$$

5) $\sigma_x > 0$, $- P_{sw} < \sigma_z < 0$.

$$E_z^{np} = \frac{1}{\frac{1-\mu^2\alpha}{E} + \frac{km\Delta w}{P_{sw}}} \quad \text{(a)} \qquad \mu_{zx}^{np} = \frac{\mu - \mu^2\alpha}{E\left(\frac{1-\mu^2\alpha}{E} + \frac{km\Delta w}{P_{sw}}\right)} \quad \text{(b)}$$

$$E_x^{np} = \frac{E}{1-\mu^2\alpha} \quad \text{(c)} \qquad \mu_{xz}^{np} = \frac{\mu + \mu^2\alpha}{1-\mu^2\alpha} \quad \text{(d)} \tag{7}$$

The swelling soil acquires orthotropic properties with deformation characteristics, determined by formulas (a) – (d).

6) $- P_{sw} < \sigma_x < 0$, $\sigma_z > 0$.

The swelling soil acquires the properties of orthotropy with deformation characteristics, determined by formulas similar to the combination 5.

7) $\sigma_x < - P_{sw}$, $\sigma_z > 0$.

$$E_x^{np} = \frac{E}{1-\mu^2} \quad \text{(a)} \qquad \mu_{xz} = \frac{\mu - \mu^2}{1-\mu^2} \quad \text{(b)}$$

$$E_z^{np} = \frac{E}{1-\mu^2} \quad \text{(c)} \qquad \mu_{zx} = \frac{\mu + \mu^2}{1-\mu^2} \quad \text{(d)} \tag{8}$$

The swelling soil acquires orthotropic properties with deformation characteristics, determined by formulas (a) – (d).

8) $\sigma_x > 0$, $\sigma_z < - P_{sw}$.

The swelling soil acquires orthotropic properties with deformation characteristics, determined by formulas 7.

9) $\sigma_x < - P_{sw}$, $\sigma_z < - P_{sw}$.

$$E_x^{np} = \frac{E}{1-\mu^2} \quad (a) \qquad \mu_{xz} = \frac{\mu - \mu^2}{1-\mu^2} \quad (b)$$

$$E_z^{np} = \frac{E}{1-\mu^2} \quad (c) \qquad \mu_{zx} = \frac{\mu - \mu^2}{1-\mu^2} \quad (d) \qquad (9)$$

Using software complexes operating on the basis of FEM, a finite element calculation scheme of the «basement – foundation – above – ground part of the structure» system is modeled in a flat version and force calculation is performed for the action of specified loads, including loading combinations. In this case, the stressed states of the base are determined, and nine zones are established where the corresponding deformation characteristics are determined and the stiffness characteristics of the finite elements are introduced into the initial information.

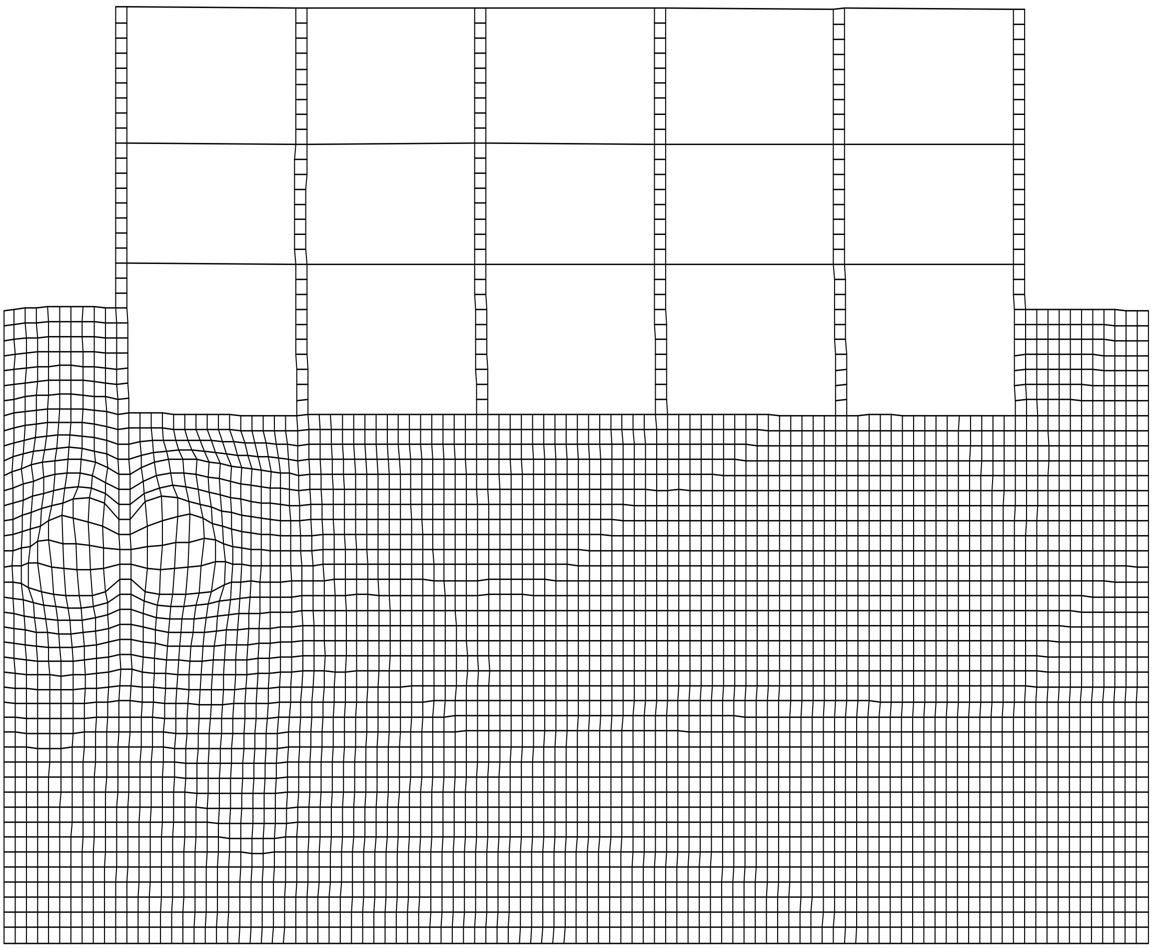

Figure 1– Deformed scheme

Further, the entire system is calculated for swelling from a change in the specified humidity, as temperature problem for temperature action equal to $m\Delta w$. The obtained stressed state of the base is summed with the stressed state from swelling and the position of the zones with different level σ_j is clarified in comparison with the swelling pressure - P_{sw}.

Then, the deformation characteristics for the new zones are refined and new calculation is performed. After calculating the new values of the total stresses, the zones are refined, etc. The calculation ends when change in the zones with different σ_j does not occur.

4. An example of swelling soils designs calculation

An example of a three-story brick building on a pile foundation in the town of Kupyansk, Kharkov Oblast, is considered. At the base there are clayeys with medium-swelling deposits at depth of 2,5 m and layer thickness of 1,5 m. Bored piles 6 m in length and 630 mm in diameter have been adopted. The base, walls and foundation are modeled by rectangular FE, 0,4×0,4 m in size. The overlap is modeled by the rod elements.

In the process of exploitation, it is possible to wet soil, and as a consequence, its swelling. It is assumed that the soaked soil works under temperature influence: $m\Delta w$ = 0,066, with a swelling ratio m = 1,237 [5].

The following results were obtained:

a) b)

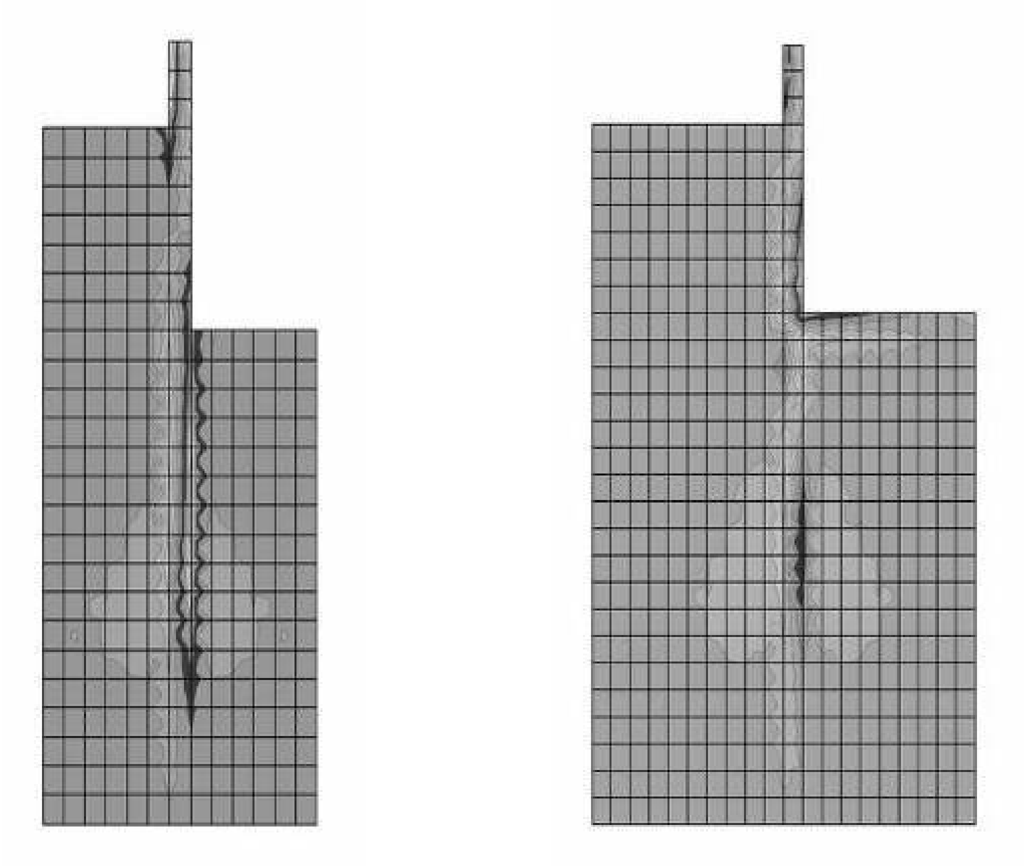

Fig.2 – Fragments of stress fields NZ
a – without considering orthotropy,
b –considering orthotropic properties of swelling soils

The difference between values of the main stresses when calculating with and without considering swelling for foundations reaches 30%, for above-ground structures - 7%.

Conclusions. 1. The swelling of the base can be considered as additional kinematic influence, close in nature to temperature.

2. The obtained solution for calculating the «basement -pile foundation-structure» system for a planar problem makes it possible to consider the orthotropic properties of swelling soils with more accurate results.

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